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(54) PROJECTION OPTICAL SYSTEM AND PROJECTION EXPOSURE APPARATUS USING SAME

(57) [Abstract]

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(54) PROJECTION OPTICAL SYSTEM AND PROJECTION EXPOSURE APPARATUS USING SAME

(57) [Abstract]

[Problems] To obtain a projection optical system in which the birefringence property of optical elements included in the projection optical system is corrected and a high-resolution pattern is obtained and a projection exposure apparatus using same.

[Means for Solving the Problems] A projection optical system for projecting a pattern of a first body on a second body, comprising birefringence correction means for correcting the birefringence property of optical elements included in the projection optical system.

[Claims]

[Claim 1] A projection optical system for projecting a pattern of the first body on the second body, said projection optical system comprising birefringence correction means for correcting the birefringence property of optical elements included in said projection optical system.

[Claim 2] The projection optical system according to claim 1, wherein said birefringence correction means is composed of one or a plurality of optical members having the prescribed form birefringence.

[Claim 3] The projection optical system according to claim 2, wherein said one or a plurality of optical members are set so that the distribution obtained by adding up the distribution of form birefringence generated thereby cancels the birefringence property generated by the optical

elements constituting said projection optical system.

[Claim 4] The projection optical system according to claim 2 or claim 3, wherein said one or a plurality of optical members generate form birefringence by using a diffraction grating having periods less than the wavelength used.

[Claim 5] The projection optical system according to claim 4, wherein said diffraction grating is provided on the surface of an optical element included in said projection optical system.

[Claim 6] The projection optical system according to claim 1, wherein said birefringence correction means is composed of one or a plurality of optical members having the prescribed distribution of stress.

[Claim 7] The projection optical system according to claim 6, wherein said one or a plurality of optical members are set so that the distribution obtained by adding the distribution of stresses generated thereby cancels the birefringence property originated from the optical elements constituting said projection optical system.

[Claim 8] A projection exposure apparatus in which the pattern present on the first body illuminated with a luminous flux from an illumination system is projected and exposed on the second body surface with the projection optical system according to any of claims 1 through 7.

[Claim 9] A projection exposure apparatus in which

the pattern present on the first body surface is illuminated with a luminous flux of a slit aperture and the pattern present on the first body surface is projected and exposed, with the projection optical system according to any of claims 1 through 7, onto the surface of the second body placed on a movable stage, while said first body and said movable stage are scanned synchronously at a speed ratio corresponding to the projection magnification of said projection optical system in the short-side direction of said slit aperture.

[Claim 10] A method for the fabrication of a device comprising a step of printing a device pattern on a substrate by using the projection exposure apparatus according to said claim 1 or claim 2.

[Detailed Description of the Invention]

[0001]

[Field of the Invention] The present invention relates to a projection optical system for the fabrication of devices such as semiconductor elements, CCD, liquid-crystal devices, and the like, to a projection exposure apparatus using the projection optical system, and to a method for the fabrication of a device by using the projection optical system. More specifically, the present invention can be advantageously used in projection exposure apparatuses (steppers) of a step-and-repeat system or a step-and-scan system in which the effect of the birefringence

property of optical elements (glass materials) comprised in the projection optical system is corrected and a high-resolution pattern is obtained.

[0002]

[Prior Art Technology] In recent years, the degree of integration of semiconductor devices such as DRAM, CPU, and the like has greatly increased and circuit patterns with a size of no more than 0.25 μm has become required in the most advanced elements (devices). The so-called steppers have been widely used as the apparatuses capable of forming such fine patterns with a high accuracy. In the stepper, the formation of a fine circuit pattern on a semiconductor wafer such as a silicon wafer is conducted by illuminating a pattern present on a reticule with a short-wave light in a UV region and projecting the pattern with a reduction on the wafer via a projection optical system.

[0003] In this process, the projection optical system has to satisfy a variety of stringent requirements in order to transfer the pattern present on the reticule with a high accuracy. Because the pattern size that can be resolved by the projection optical system is inverse proportional to a NA (numerical aperture), a design increasing the NA is required. Furthermore, it is necessary to correct the aberration with a high efficiency over the entire region corresponding to the surface area of a semiconductor device.

[0004] Such a design can be implemented with a high-speed computer and a special design software. When the projection optical system is manufactured, each lens constituting the projection optical system obviously has to be processed with a high accuracy according to the design parameters, but much attention has to be also paid to the glass material used therein. The refractive index of the glass material is strongly correlated with the image forming characteristic of the projection optical system. Therefore, the uniformity thereof is closely controlled and usually a uniformity level of no more than 10^{-6} is attained. Moreover, it is known that because the birefringence property of glass material also produces a significant effect on the image forming characteristic, the value thereof has to be suppressed to about 2 nm/cm.

[0005] However, in the glass materials for projection optical systems whose maximum diameter sometimes reaches 200 mm, such a highly accurate control of birefringence property is very difficult to conduct uniformly over the entire surface and usually a certain birefringence property appears due to the reasons as follows.

[0006] The first reason is associated with the process for the manufacture of glass materials. Because quartz glass is widely used at present as a glass material for lens elements with respect to light in a UV region, the explanation hereinbelow will be focused on quartz glass.

By contrast with optical crystals, quarts glass used as a glass material has no structural directivity. Therefore, no birefringence property is observed in an ideal state.

[0007] However, the birefringence property apparently caused by residual stresses induced by impurities, thermal history, and the like can be experimentally observed in quartz glass. A direct method, a VAD (vapor axial deposition) method, a sol-gel method, a plasma burner method, and the like are used for the manufacture of high-quality quartz glass for lithography. With all of those methods, the introduction of impurities is very difficult to suppress to a negligibly small level by the presently available technology.

[0008] Furthermore, when the quartz glass formed in a high-temperature state is cooled, the stresses generated by the difference in cooling on the surface and in the central part, that is, the stresses caused by thermal history, are in principle very difficult to reduce entirely to zero, though a certain relaxation thereof can be attained by heat treatment such as annealing or the like.

[0009] The process for the fabrication of lens elements used in the projection optical system during lithography will be explained hereinbelow with reference to FIG. 24. First, an ingot 100 of quartz glass is formed so as to have a rotation symmetrical shape, and a disk-like member 101 is obtained by cutting the ingot to the required

thickness. Because the manufacture of ingot 100 is usually conducted in the shape symmetrical with respect to a central axis 100a, the distribution of impurities remaining in the member 101 and the distribution of stresses caused by thermal history obviously also assume a shape symmetrical with respect to the central axis 101a. A lens element 102 is finally produced machining (cutting and polishing) of the member 101.

[0010] Strains appearing in the ingot 100 due to the admixture of impurities will be explained hereinbelow. FIG. 25 shows a cut surface of ingot 100. The concentration of impurities is assumed to be increased in the peripheral hatched portion 103. The ingot 100 is heated in the annealing process. In a state in which heat is applied, the internal stresses are almost entirely reduced to zero and subsequent gradual cooling from this state, in the ideal situation, produces a material with zero internal stresses even at room temperature. However, if impurities are admixed, the thermal expansion coefficient of the material changes. If we consider that the thermal expansion coefficient is increased by admixed impurities, then shrinkage of this portion in the cooling process will obviously increase.

[0011] Therefore, reducing the temperature of a material that had no stresses in a heated state will result in a lager shrinkage in the peripheral portions. Observations of the central portion of a glass material

transmitting a luminous flux demonstrate that it is subjected to compression from the periphery as shown by arrows in FIG. 25, generating internal stresses. The internal stresses result in birefringence property.

[0012] The second reason is associated with changes in quartz glass with time during utilization in a stepper. Illuminating quartz glass with light from a short-wave light source such as a KrF or ArF laser is known to cause an effect caused compaction. Detailed explanation of the origination of this effect is omitted, but the increase in refractive index and volume shrinkage in the zone through which the luminous flux has been transmitted can be mentioned as the effects observed.

[0013] If a hatched region 111 in the disk-like glass material 110 shown in FIG. 26 is illuminated with laser radiation, then the volume of this region will be reduced. Because the peripheral portion which is not illuminated with laser radiation is obviously not affected by compaction, as a whole, the zone close to the center will shrink, whereas the shrinkage of the zone close to the periphery will be hindered.

[0014] Therefore, in the equilibrium state, in the central portion of the glass material transmitting a luminous flux, tensile forces, such as shown by the arrows in FIG. 27, are received from the periphery and the internal stresses are generated. The internal stresses result in the

birefringence property. The above-described effects similarly occur in projection optical systems of steppers. An especially significant compaction appears under illumination with ArF laser radiation, which may become a significant problem in subsequent transition to practical use of projection exposure apparatuses using ArF laser radiation as a light source.

[0015]

[Problems to be Solved by the Invention] As described hereinabove, it is actually difficult to completely reduce to zero the birefringence property induced in a glass material. In this respect, the requirements relating to birefringence in the projection optical systems for steppers are getting more and more stringent. In order to realize a projection optical system with better performance, the number of lens elements constituting a projection optical system is increased which results in the increased total thickness of glass material. As a result, even if the quantity of birefringence per unit length is suppressed to the above-mentioned value (about 2 nm/cm) the quantity of birefringence of the entire structure assumes a value that cannot be ignored. Furthermore, the transition to progressively shorter wavelengths for exposure light sources also serves to increase the effect of birefringence property.

[0016] More specifically, let us compare the i

radiation source (wavelength 365 nm) used in the projection exposure apparatuses and the ArF laser light source (wavelength 193 nm). For example, when the birefringence property is 100 nm for the entire optical system, with respect to i radiation with a wavelength or 365 nm, it is equivalent to a wave front aberration of 100/365 = 0.27 wavelength, whereas with respect to the ArF laser light source with a wavelength of 193 nm, it is equivalent to a wave front aberration of 100/193 = 0.52 wavelength. Thus, it is clear that even if the birefringence property of the same value is assumed, the effect produced on the image forming characteristic becomes larger for shorter wavelengths.

[0017] Japanese Patent Application Laid-open No. H8-107060 describes that the negative effect produced on optical characteristics in an optical glass material having a birefringence property with a central symmetry can be somewhat reduced by using glass materials with different birefringence values for all lens elements and optimizing the combination of the glass materials. With such an approach, however, the requirements on the increase in accuracy placed on the projection optical systems cannot be met. Accordingly, it is necessary to cancel the birefringence property of glass materials in itself by some means.

[0018] It is an object of present invention to provide a projection optical system in which installing a

birefringence correction member for correcting the birefringence property that has been set appropriately in the projection optical system makes it possible to correct reliably the birefringence property of the projection optical system and the birefringence property induced in the process of conducting the projection exposure, this projection optical system being capable of transferring highly accurate patterns, a projection exposure apparatus using such a projection optical system, and a method for the fabrication of devices by using such a projection exposure apparatus.

[0019]

[Means for Solving the Problems] The projection optical system in accordance with the present invention is (1-1) a projection optical system for projecting a pattern of the first body on the second body, the projection optical system comprising birefringence correction means for correcting the birefringence property of optical elements included in the projection optical system.

[0020] In particular, (1-1-1) the birefringence correction means is composed of one or a plurality of optical members having the prescribed form birefringence.

[0021] (1-1-2) The above-mentioned one or a plurality of optical members are set so that the distribution obtained by adding up the distribution of form birefringence generated thereby cancels the birefringence

property generated by the optical elements constituting the projection optical system.

[0022] (1-1-3) The above-mentioned one or a plurality of optical members generate form birefringence by using a diffraction grating having periods less than the wavelength used.

[0023] (1-1-4) The diffraction grating is provided on the surface of an optical element included in the projection optical system.

[0024] (1-1-5) The birefringence correction means is composed of one or a plurality of optical members having the prescribed distribution of stress.

[0025] (1-1-6) The above-mentioned one or a plurality of optical members are set so that the distribution obtained by adding up the distribution of stresses generated thereby cancels the birefringence property generated by the optical elements constituting the projection optical system.

[0026] The projection exposure apparatus in accordance with the present invention is (2-1) a projection exposure apparatus in which the pattern present on the first body illuminated with a luminous flux from an illumination system is projected and exposed on the second body surface with the projection optical system with configuration according to clause (1-1).

[0027] (2-2) A projection exposure apparatus in

which the pattern present on the first body surface is illuminated with a luminous flux of a slit aperture and the pattern present on first body surface is projected and exposed, with the projection optical system with configuration according to clause (1-1), onto the surface of the second body paced on a movable stage, while the first body and the movable stage are scanned synchronously at a speed ratio corresponding to the projection magnification of the projection optical system in the short-side direction of the slit aperture.

[0028] (3-1) The method for the fabrication of a device in accordance with the present invention comprises a step of printing a device pattern on a substrate by using the projection exposure apparatus with configuration according to clause (2-1) or (2-2).

[0029]

[Preferred Embodiments of the Invention] FIG. 1 is a cross-sectional view of the main part of the projection optical system in accordance with the present invention. The present embodiment is applicable to a step-and-repeat or step-and-scan system. In the figure, the reference symbol PL stands for a projection optical system usually composed of several tens of optical elements in which aberration has been corrected with a high accuracy. For the sake of simplicity, those optical elements are represented by lens elements 1-5 in the figure.

[0030] The lens elements 1-5 are formed by cutting and polishing quartz glass. The configuration in which the projection optical system PL has actually been installed in a stepper will be explained hereinbelow in greater detail. The reference numerals 6 and 7 stand for a reticule and a wafer, respectively. The pattern present on the surface of reticule 6 is projected, with a reduction based on a step-and-repeat system or step-and-scan system, onto the surface of wafer 7 by the projection optical system PL.

[0031] In the figure, the reference numeral 8 stands for a birefringence correction member in accordance with the present invention. The operation thereof will be explained hereinbelow in greater detail.

[0032] As described above, in the manufacture of quartz glass serving as a material for lens elements 1-5, the appearance of strains symmetrical with respect to the central axis is difficult to suppress entirely. Alternatively, when the elements are used in combination with a short-wave light source such as an ArF laser or the like, strains appear under he effect of volume shrinkage caused by compaction. The effects produced when such strains appear in glass material will be explained hereinbelow. First, stresses generated by the strains will be explained with reference to FIG. 2.

[0033] In FIG. 2, the reference numeral 10 stands for a disk cut from the quartz glass ingot so as to have

the prescribed height h, this disk being a glass material at a stage prior to processing into a lens element. The reference numeral 11 stands for a central axis of disk 10. Further, the x, y, z coordinate axes are set as shown by the reference numeral 12. In such a case, stresses in the direction (z direction) along the central axis 11 can be ignored. Therefore, as shown in FIG. 3, the attention should be paid only to stress σ_r in the radial direction and stress σ_θ in the circumferential direction in the point P represented by polar coordinates (r, θ) in the xy plane. If the balance of forces in the radial direction is considered for a very small region 13 shown by hatching in the vicinity of point P, then the following relationship is obtained: $-\sigma_r \cdot rd\theta + (\sigma_r + d\sigma_r)(r + dr)d\theta - \sigma_\theta d\theta \cdot dr = 0$. Omitting the high-order small quantities, we obtain the following relationship: $\sigma_\theta - \sigma_r = r(d\sigma_r/dr)$ ... (1).

[0034] Because the strains remaining in the glass material 10 change in the radial direction, the derivative of σ_r with respect to r is typically not equal to zero. For this reason, the right side of Formula (1) assumes a limited value not equal to zero if $r \neq 0$ (outside the central axis). This result indicates that the stress σ_r in the radial direction r and stress σ_θ in the circumferential direction assume different values outside the central axis 11.

[0035] The effects that are optically observed in such a case will be explained with reference to FIGS. 4 and

5. Let us assume that a luminous flux that was linearly polarized in the y direction and has a wavelength l comes in the position of point P (r, θ), as shown in FIG. 4. Here, the polarization direction of the linearly polarized light is shown by an arrow 14. When the incident light is transmitted through the disk 10, the polarized component 15 in the radial direction and the polarized component 16 in the circumferential direction undergo refraction with different refractive indexes. As a result, after transmission through the disk 10, a phase difference Φ is generated between the two polarization components, and the polarization state of the luminous flux is transformed from the linear polarization to the elliptical polarization as shown in FIG. 5. By using stresses σ_r, σ_θ, phase difference Φ in this case can be represented by $\Phi(r) = (2\pi/\lambda)C \cdot h\{\sigma_\theta(r) - \sigma_r(r)\}$ ... (2).

[0036] The reference symbol C denotes the value inherent to a substance and called a photoelastic constant. Thus, if a luminous flux is transmitted through the disk-like glass material 10, the polarization state thereof changes. The effect observed in each single glass material is obviously very small. However, after the luminous flux has been transmitted through several tens of elements, an adverse effect that cannot be ignored is produced on the image forming characteristic of the projection optical system. If the effect represented by formula (2) is considered for each

element in a real projection optical system and the quantities of phase changes caused by the birefringence property are added up for the entire projection optical system, a graph shown in FIG. 6 is obtained.

[0037] Here, a pupil coordinate ρ of the optical system is plotted instead of the radius r of lens elements on the abscissa. The pupil coordinate will be explained with reference to FIG. 7. The reference numerals 17, 18 in the figure stand for lens elements. Let us consider a light beam 19 transmitted through the lens elements 17, 18. A large number of parameters are required in this case to designate the position of the light beam, for example, a radius r_1 measured from the central axis (optical axis) 20 in the lens element 17 and a radius r_2 measured from the central axis 20 in the lens element 18, which is inconvenient.

[0038] For this reason, if we consider the pupil position 21 of the entire optical system and designate the light beam 19 by the pupil coordinate ρ representing the height of the light beam 19 that passes thereby, then the characteristics of the optical system can be represented with a single parameter. Here, ρ specifies the position of a luminous flux transmitted through the optical system as a pupil coordinate, and the maximum value thereof is considered to be ρ_0.

[0039] The results shown in FIG. 6 can be experimentally measured by using the actually assembled

optical system, with appropriate means such as a phase modulation method or the like. However, they can be also computed by simulation at a certain sacrifice of accuracy. The phase modulation method is described in detail, for example, by Etsuhiro Matsuda in Kogijutsu Contact, vol. 27, No. 3 (1989). For this reason, the explanation thereof will be herein omitted. The method has a very high sensitivity and measurements with an accuracy of 10^{-8} can be conducted with a value of refractive index difference Δn caused by the birefringence property. Another advantage of the method is that the phase lead axis and phase lag axis can be determined at the same time.

[0040] If the phase lead axis and phase lag axis are known, the sign of Φ (ρ) in FIG. 6 can be directly determined. In any case, data shown in FIG. 6 demonstrate that the change in phase caused by the birefringence property in the luminous flux transmitted through the center ($\rho = 0$) of optical system is zero, whereas the change in phase caused by the birefringence property in the luminous flux transmitted through the peripheral zone ($\rho = \rho_0$) reaches $\pi/4$.

[0041] Omitting the comprehensive explanation of the effect produced on the image forming characteristics, which uses the theoretical formulas, we will note that phenomenologically an astigmatism with a size of about $\lambda/4$ appears in the optical system. The aberration allowed in the projection optical systems for steppers is of an order

of $\lambda/100$, and the aberration of the above-mentioned size cannot possibly be allowed.

[0042] In accordance with the present invention, the phase change component such as shown in FIG. 6 is canceled by using a birefringence correction member 8 in the optical system shown in FIG. 1. It is clear that a member with a birefringence property of an inverse sign may be used symmetrically with respect to the optical axis in order to cancel the birefringence generated symmetrically with respect to the optical axis. However, the quantity of this birefringence has to be identical to that of the birefringence generated in the entire projection optical system PL.

[0043] The specific configuration of birefringence correction member 8 will be described below. Because the material of the birefringence correction member has to be transparent to the exposure light and has to have a sufficient endurance, it is necessary to use an optical glass similar to that employed for the lens elements 1-5. An effect referred to herein as form birefringence is used to generate the birefringence property with the prescribed distribution in such an optical glass.

[0044] First, the form birefringence will be described with reference to FIG. 8. In the figure, the reference numeral 25 stands for a phase-type diffraction grating formed on the surface of optical glass. The

diffraction grating 25, as also shown on an enlarged scale in the right part of the drawing, has a period (b) and a depth (d); the width of the portion of optical glass forming the fine grating is (a). The duty ratio, t, which is to be used in the following discussion is defined as $t = a/b$. The reference numeral 26 stands for an incoming luminous flux (wavelength : λ) that falls onto such diffraction grating 25, and the reference numeral 27 stands for an outgoing luminous flux which comes out of this diffraction grating.

[0045] Further, the reference numeral 28 stands for a polarization component in the direction parallel to the grooves of diffraction grating 25 and the reference numeral 29 stands for a polarization component in the direction perpendicular to the grooves of diffraction grating 25, with respect to the incoming luminous flux 26. Similarly, the reference numeral 30 stands for a polarization component in the direction parallel to the grooves of diffraction grating 25 and the reference numeral 31 stands for a polarization component in the direction perpendicular to the grooves of diffraction grating 25, with respect to the outgoing luminous flux 27.

[0046] As for the period b of diffraction grating 25, the requirement that "b is no more than λ" has to be satisfied so that no diffraction light other than 0-order light is generated as the outgoing light 27.

[0047] FIG. 8 demonstrates that a phase difference Ψ is generated between the polarization components 30 and 31 when the incoming light 26 with a phase difference between the polarization components 28, 29 transmitted through the diffraction grating 25. Therefore, if we assume that the incoming light 26 is a linearly polarized light, it can be understood that the outgoing light 27 is transformed into an elliptically polarized light. This effect is called "form birefringence" and it has been known for a long time in the field of optics.

[0048] For example, a comprehensive explanation of this effect is given in the following references: M. Born and E. Wolf : Principles of Optics, 1st ed. (Pergamon Press, New York, 1959) pp. 705-708, Aoyama et al. Birefringence Elements Using Fine Diffraction Gratings and Application Thereof, Kogaku, Vol. 21, No. 5 pp. 269-274 (1992). The contents thereof will be summarized below.

[0049] In the fine diffraction grating 25 such as shown in FIG. 8, refractive indexes are demonstrated that differ depending on the polarization direction of incoming luminous flux 26. The refractive index $n_{\parallel}$ relating to the case when the polarization of incoming light 26 is parallel to the grooves of diffraction grating 25 and the refractive index $n_{\perp}$ relating to the case when the polarization of incoming light 26 is perpendicular to the grooves of diffraction grating 25 can be represented as follows

[0050]

[Formula 1]

... (3)

... (4)

Here, t is the duty ratio defined hereinabove, n_1 is the refractive index of the member constituting the diffraction grating 25 and n_2 is the refractive index of the medium on the incoming side of luminous flux. The results obtained in calculating the dependence $n_{\parallel}$ and $n_{\perp}$ on t are shown in FIG. 9 for $n_1 = 1.6$ and $n_2 = 1.0$. Further, if the depth of the grooves in the diffraction grating 25 is denoted by d, then the phase difference Ψ appearing between the polarization component parallel to the grooves of diffraction grating 25 and the polarization component perpendicular to the grooves of diffraction grating can be represented by the following formula.

[0051]

[Formula 2]

$$\Psi = 2\pi d/\lambda(n_{\parallel} - n_{\perp}) \quad \text{... (5)}$$

[0052] Formulas (3) – (5) demonstrate that the phase difference Ψ can be set to any value by appropriately selecting the duty ratio t and groove depth d.

[0053] Further, a specific configuration will be explained in which the birefringence correction member 8 is inserted into the pupil position 21 of projection optical

system PL shown in FIG. 7. The explanation will be conducted with reference to FIG. 10.

[0054] FIG. 10 serves to explain the phase difference between the polarization component in the radial direction and the polarization component in the circumferential direction in the case when the luminous flux designated by the pupil radius ρ is transmitted through the lens elements 1 - 5 and birefringence correction member 8 in the projection optical system shown in FIG. 1. Under an assumption that the birefringence property is symmetrical with respect to the optical axis in the glass material, the appearance of phase difference between the polarization component in the radial direction and the polarization component in the circumferential direction of the incoming light was explained using FIG. 4 and FIG. 5.

[0055] In FIG. 10, the reference numerals 41-44 stand for polarization components in the radial direction, and the reference numerals 45-48 stand for polarization components in the circumferential direction. The phase difference therebetween is obviously zero before the luminous flux 40 falls onto the lens element 1.

[0056] In this case, an assumption is made that in the entire projection optical system, the phase difference $\Phi(\rho)$ shown in FIG. 6 appears as the function of pupil radial coordinate □ due to the birefringence property generated in each lens element 1-5. Furthermore, if $\Phi(\rho)$ is laid out

as $\Phi(\rho) = \Phi_1(\rho) + \Phi_2(\rho)$, then the phase difference $\Phi_1(\rho)$ is assumed to be the phase difference generated by the lens elements 1-3 and the phase difference $\Phi_2(\rho)$ is assumed to be the phase difference generated by the lens elements 4-5.

[0057] Further, an assumption is made that in the birefringence correction member 8 the phase difference $\Psi(\rho)$ between the polarization components in the radial direction and circumferential direction appears as a function of pupil coordinate ρ. Under such an assumption, the phase difference between the polarization components in the radial direction and circumferential direction in the luminous flux immediately prior to incidence upon the birefringence correction member 8 will be represented by $\Phi_1(\rho)$, the phase difference immediately after the light has been transmitted through the birefringence correction member 8 will be represented by $\Phi_1(\rho) + \Psi(\rho)$, and the phase difference after the light has been transmitted through the lens elements 4-5 will be represented by $\Phi_1(\rho) + \Phi_2(\rho) + \Psi(\rho) = \Phi(\rho) + \Psi(\rho)$ ... (6).

[0058] The essence of the present invention is in inserting into an optical path a member having the birefringence property capable of providing the phase difference function $\Psi(\rho)$ which zeros Formula (6).

[0059] Considering also FIG. 6, it becomes clear that the phase difference function $\Psi(\rho)$ which zeros Formula (6) becomes the function shown in FIG. 11. In other words, it

has an absolute value identical and the sign opposite to those of the phase difference $\Phi(\rho)$.

[0060] As described hereinabove, using the fine diffraction grating 25 which demonstrates a form birefringence and appropriately selecting the duty ratio t and groove depth d of the diffraction grating make it possible to set the phase difference between the polarization component in the direction parallel to the grooves of the diffraction grating and the polarization component in the direction perpendicular to the grooves of the diffraction grating to an arbitrary value.

[0061] Here, a fine diffraction grating is formed so as to be symmetrical with respect to the optical axis on the surface of the birefringence correction member 8. In this case, a configuration in which the diffraction grating 25 is arranged in the form of concentric rings around the optical axis, as shown in FIG. 12, or a configuration in which the diffraction grating 25 is arranged radially with respect to the optical axis, as shown in FIG. 13, are possible.

[0062] It has already been mentioned hereinabove, that the only condition required for the period of the fine diffraction grating necessary to generate a form birefringence is that this period be no more than the wavelength λ. However, if the period is too small, the manufacturing process becomes difficult. Accordingly, it

is desired that the period of the diffraction grating be confined within a range of $\lambda/3$-λ. For this purpose, in the configuration in which the diffraction grating is arranged radially with respect to the optical axis, the radial direction is divided into a plurality of regions, as shown in FIG. 13, and the periods within each of the regions are confined in the aforesaid range.

[0063] The difference in functions caused by the difference in configurations shown in FIG. 12 and FIG. 13 will be described below. As for the phase difference between the polarization component 50 in the radial direction and polarization component 51 in the circumferential direction in the luminous flux incident upon point P in FIG. 12, transmitting the light through the member 8 can delay the phase of the polarization component 51 in the circumferential direction with respect to the phase of the polarization component 50 in the radial direction. On the other hand, considering the structure shown in FIG. 13 in a similar manner suggests that the phase of polarization component 53 in the circumferential direction can be advanced with respect to the phase of the polarization component 52 in the radial direction. Thus, the two configurations can be used separately according to the sign of the birefringence property generated in the projection optical system. In order to generate the phase difference $\Psi(\rho)$ shown in FIG. 11, the structure shown in FIG. 13 is preferably used.

[0064] The correction amount of the phase obviously has to be changed in the radial direction. For this purpose, the duty ratio or the groove depth in the fine diffraction grating may be changed. However, because from the standpoint of manufacturing process, the duty ratio is very difficult to change in a continuous manner, the configuration in which the groove depth is changed will be described below with reference to FIG. 14. FIG. 11 also clearly shows that the phase correction amount is zero on the optical axis of the optical system. Therefore, as shown in FIG. 14, a structure may be used in which the depth of the grooves in the fine diffraction grating is zero in the vicinity of the central axis and decreases toward the peripheral zones.

[0065] The position into which the birefringence correction member 8 is inserted is preferably close to the pupil position of the projection optical system, but such an arrangement is not limiting. Furthermore, in the present embodiment the explanation was provided with respect to the case in which a parallel flat plate was used as the birefringence correction member, but the shape of the birefringence correction member is not limited to the parallel flat plate and it may have a convex or concave shape as the usual lens element.

[0066] FIG. 15(A) illustrates an example in which a fine diffraction grating in the form of rings concentrically arranged with respect to the central axis

is formed on the convex surface. FIG. 15(B) illustrates an example in which a fine diffraction grating is formed radially with respect to the central axis on the convex surface. Further, in the present embodiment, the explanation was conducted with respect to the case in which the birefringence correction member is composed of a single optical element, but the birefringence correction amount may be also partitioned between a plurality of members.

[0067] In this case, a larger birefringence property generated in the projection optical system or a birefringence property having a more complex distribution can be corrected.

[0068] FIG. 16 is a schematic view illustrating the main part of Embodiment 2 in which the projection optical system in accordance with the present invention is installed in a stepper. In this figure, the reference numeral 60 stands for a reticule having a circuit pattern drawn thereupon, 61 - the projection optical system in accordance with the present invention, and 62 - a wafer onto which the circuit pattern is to be transferred. An illumination luminous flux 63 from an illumination system 67 illuminates an illumination region 64 on the reticule 60, and the circuit pattern drawn on this region 64 is transferred with a reduction onto an exposure region 65 on the wafer 62 via the projection optical system 61. In the stepper, once the pattern present on the reticule 60 has been transferred with a reduction onto the wafer 62, the

wafer 62 is stepped by the prescribed quantity and the exposure is repeated again.

[0069] The reference numeral 66 in the figure stands for a birefringence correction member. The specific feature of this configuration is that the birefringence correction member 66 itself can be removed and replaced so as to allow the correction quantity to be adjusted according to the birefringence quantity of the projection optical system 61.

[0070] FIG. 17 is a schematic view of the main part of Embodiment 3 in which the projection optical system in accordance with the present invention is installed in a step-and-scan exposure apparatus. In this figure, the reference symbol 70 stands for a reticule having a circuit pattern drawn thereupon, 71 - a projection optical system, 72 - a wafer onto which the circuit pattern is to be transferred. An illumination luminous flux 73 from an illumination system 67 illuminates an illumination region 74 on the reticule 70, and the circuit pattern drawn on this region 74 is transferred at once with a reduction onto an exposure region 75 on the wafer 72 via the projection optical system 71. The step-and-scan exposure apparatus is different from the conventional stepper in the following respects.

[0071] In the stepper, the pattern present on the reticule 70 is at once transferred with a reduction onto the wafer 72, whereas in the step-and-scan exposure apparatus

the circuit pattern is illuminated in a slit-like illumination region 74 and the entire circuit pattern present on the reticule 70 is transferred with a reduction by scanning the reticule 70 and wafer 72 synchronously.

[0072] In the system of coordinates represented by the reference numeral 76, the scanning direction 77 of reticule 70 is the negative direction of the x axis, and the scanning direction 78 of wafer 72 is the positive direction of the x axis. The reference numeral 79 in the figure stands for a birefringence correction member which can be removed and replaced in the same manner as in the stepper.

[0073] In the step-and-scan exposure apparatus, the illumination region 74 has a slit-like shape. Therefore, the effect of compaction induced by illumination, for example, with the ArF laser light is not demonstrated symmetrically with respect to the optical axis.

[0074] The light transmission region in the lens element in the projection optical system 71 will be explained hereinbelow with reference to FIG. 18. In the figure, the reference numeral 80 stands for a representative lens element arranged in the xy plane (the reference numeral 81 denotes the coordinate axes).

[0075] In the lens element 80, the region through which the luminous flux is transmitted also has a shape extending in the y axis direction, as shown by a hatching

82, corresponding to the shape of the illumination region 74 shown in FIG. 17. Therefore, the strains caused by the compaction are also generated correspondingly to this shape. The birefringence property of the optical system, which is generated as a result of such strain generation, is obviously also asymmetrical with respect to the optical axis.

[0076] The quantity of phase changes caused by birefringence is shown in FIG. 19 in the representation using pupil coordinates similar to those used in FIG. 6. Thus, different distributions are obtained in the x axis direction and y axis direction. In order to correct such a distribution of birefringence quantity, the distribution of groove depth illustrated by FIG. 14 can be correlated thereto by making it different in the x axis direction and y axis direction.

[0077] Embodiment 2 of the birefringence correction member in accordance with the present invention will be described hereinbelow. In the Embodiment 1 shown in FIGS. 1 through 8, because the material of the birefringence correction member was required to be transparent with respect to the exposure light and to have a sufficient endurance, a glass identical to the optical glass used for the lens elements 1-5 was used in the specific configuration of birefringence correction member 8, and the effect of form birefringence was used to generate the birefringence property.

[0078] By contrast with the Embodiment 1, in the

present embodiment, strains remained in the manufacture of optical glass and the birefringence property was demonstrated under the effect of those strains, as has already been explained hereinabove, but here the optical glass is actively provided with the strains in order to generate the desired birefringence property. This is the only difference between this embodiment and Embodiment 1; other structural features and utilization mode thereof are basically the same.

[0079] Strains are caused to remain in the optical glass by conducting accurate temperature control in the annealing process. The term annealing usually relates to a process conducted to relieve strains remaining in optical glass, whereas in the fabrication of the birefringence correction member in accordance with the present invention, the annealing process is conversely used to generate the residual strains.

[0080] The annealing process will be described hereinbelow with reference to FIG. 20. In the figure, the reference numeral 130 stands for an optical member serving as a preform for the birefringence correction member 8. The optical member 130 has a round disk-like shape, and the position on the member is designated by the distance r from a central axis 131.

[0081] FIG. 20(A) represents a state prior to heating in the annealing process. FIG. 20(B) represents a state

in which heat was uniformly provided to the entire optical member 130. In this state, practically no stress distribution exists inside the optical member 130, but a large stress distribution can be generated in the cooling process illustrated by FIGS. 20(C) and 20(D). As shown in FIG. 20(C), the optical member 130 is returned to the state at room temperature by rapidly cooling by blowing air in the vicinity of the center and then large residual stresses are generated inside the optical member. This stress distribution is shown in FIG. 20(E).

[0082] The stress s_r in the radiation direction r and the stress s_q in the circumferential direction are shown as functions of radius r. In the center, the stresses match each other and the difference therebetween clearly increases as the radius r increases. If a body in which such a stress difference is present is inserted into an optical path, then a phase difference that can be calculated by Formula (2) is generated.

[0083] The stress distribution generated in the optical member is adjusted so as to assume a value canceling the phase difference caused by the birefringence property of the entire projection optical system shown in FIG. 6. For this purpose it is necessary to conduct a stringent control of the temperature of the gas employed for blowing, the blowing position, and the temperature after the gas blowing. Optimum conditions for those parameters can be

found by repeated tests. For example, the stress distribution shown in FIG. 20(F) can be obtained by conducting rapid cooling by blowing a gas on the periphery as shown in FIG. 20(D).

[0084] A similar effect can be obtained by changing the concentration of impurities in the optical member 130 in the radial direction instead of controlling the temperature distribution in the annealing process as the method for causing the generation of residual stresses in the birefringence correction member 8. Furthermore, it goes without saying that the desired internal stress distribution can be provided by applying mechanical pressure from the outside to the disk-like glass material or lens element.

[0085] In the exposure apparatus of the step-and-scan type shown in FIG. 17, the birefringence property asymmetrical with respect to the optical axis is generated in the projection optical system. A method for correcting the asymmetrical birefringence property by using the birefringence correction plate of the present embodiment in the above-described exposure apparatus will be explained hereinbelow with reference to FIG. 21.

[0086] Here, the adjustment of the birefringence property of the correction member is conducted by controlling the temperature distribution during annealing, similarly to the method explained with reference to FIG. 20. In FIG.

21, the reference numeral 163 represents a state in which uniform heat was supplied to the entire body in the annealing process, 164 – a state after providing different temperature distributions in the x direction and y direction and cooling. In this state the residual strains in the member have different distributions in the x direction and y direction, and inserting such a member into a projection optical system corrects the effect of birefringence generated asymmetrically with respect to the light axis of the optical system.

[0087] The implementation of the method for the fabrication of semiconductor devices by using the projection exposure apparatus described hereinabove will be described hereinbelow.

[0088] FIG. 22 is a flow chart of the method for the fabrication of semiconductor devices (semiconductor chips such as IC or LDI and the like, or liquid-crystal panels, CCD, and the like).

[0089] In step 1 (circuit design), a circuit design of a semiconductor device is conducted. In step 2 (mask fabrication), a mask having formed thereon the designed circuit pattern is fabricated.

[0090] On the other hand, in step 3 (wafer manufacture), a wafer is manufactured using a material such as silicon or the like. Step 4 (wafer process) is called preprocessing; in this step, an actual circuit is formed

on the wafer by lithography by using the above-described prepared mask and wafer.

[0091] The next step 5 (assembly) is called after-processing. In this process, a semiconductor chip is obtained by using the wafer fabricated in step 4. This step includes an assembly process (dicing, bonding), a packaging process (chip sealing), and the like.

[0092] In step 6, the inspection of the semiconductor device fabricated in step 5 is conducted, this inspection comprising the operation confirmation test, endurance test, and the like. The above-described process produces the semiconductor device which is then shipped (step 7).

[0093] FIG. 23 is a detailed flow chart of the aforesaid wafer process. In step 11, the wafer surface is oxidized. In step 12 (CVD), an insulating film is formed on the wafer surface.

[0094] In step 13, electrodes are formed on the wafer by deposition. In step 14 (ion implantation), ions are implanted into the wafer. In step 15 (resist treatment), a photosensitizer is coated on the wafer. In step 16 (exposure), a circuit pattern of the mask is baked and exposed on the wafer with the above-described exposure apparatus.

[0095] In step 17 (development), the exposed wafer is developed. In step 18 (etching), portions outside the developed resist are etched out. In step 19 (resist peeling), the resist that became unnecessary upon completion of etching

is removed. Multiple formation of circuit patterns on the wafer is conducted by repeating the above-described steps.

[0096] With the fabrication method of the present embodiment, semiconductor devices with a high degree of integration that were difficult to fabricate by the conventional technology can be fabricated in an easy manner.

[0097]

[Effect of the Invention] With the present invention, as described hereinabove, providing a birefringence correction member for correcting the birefringence property that has been set appropriately in the projection optical system makes it possible to correct reliably the birefringence property of the projection optical system and the birefringence property generated in the process of conducting the projection exposure process, this projection optical system being capable of transferring highly accurate patterns, a projection exposure apparatus using such a projection optical system, and a method for the fabrication of devices by using such a projection exposure apparatus.

[0098] In particular, even when the birefringence property appears in a glass material constituting the projection optical system, the present invention makes it possible to correct the effect thereof and to transfer highly accurate patterns. An additional effect is that the effect of strains caused by compaction produced when the glass material absorbs light from an ArF laser or the like can

be also corrected.

[Brief Description of the Drawings]

FIG. 1 is a schematic view illustrating the cross section of the projection optical system of Embodiment 1 of the present invention.

FIG. 2 illustrates the effect of residual strains of optical elements.

FIG. 3 illustrates the effect of residual strains of optical elements.

FIG. 4 illustrates the effect of the birefringence property of optical elements.

FIG. 5 illustrates the effect of the birefringence property of optical elements.

FIG. 6 illustrates the phase difference generated by the birefringence property of glass material in accordance with the present invention.

FIG. 7 illustrates the pupil coordinates of the optical system.

FIG. 8 illustrates the form birefringence of Embodiment 1 of birefringence correction means in accordance with the present invention.

FIG. 9 illustrates the difference in refractive index caused by the direction of polarization.

FIG. 10 illustrates phase changes caused by birefringence in accordance with the present invention.

FIG. 11 is the distribution of phase variation quantity

generated by the birefringence correction member.

FIG. 12 illustrates the birefringence correction member using the form birefringence in accordance with the present invention.

FIG. 13 illustrates the birefringence correction member using the form birefringence in accordance with the present invention.

FIG. 14 illustrates the depth distribution of the fine diffraction grating in accordance with the present invention.

FIG. 15 is a fine diffraction grating formed on a convex surface in accordance with the present invention.

FIG. 16 is a schematic view of the main part of the stepper of Embodiment 2 in accordance with the present invention.

FIG. 17 is a schematic view illustrating the main part of the projection exposure apparatus of a step-and-scan type of Embodiment 3 in accordance with the present invention.

FIG. 18 illustrates the asymmetrical strain distribution generated in the projection exposure apparatus of a step-and-scan type of Embodiment 3 in accordance with the present invention.

FIG. 19 illustrates the asymmetrical strain distribution generated in the exposure apparatus of a step-and-scan type of Embodiment 3 in accordance with the present invention.

FIG. 20 schematically illustrates the main part of Embodiment 2 of birefringence correction means in accordance with the present invention.

FIG. 21 schematically illustrates the main part of Embodiment 2 of birefringence correction means in accordance with the present invention.

FIG. 22 is a flow chart of the method for device fabrication in accordance with the present invention.

FIG. 23 is a flow chart of the method for device fabrication in accordance with the present invention.

FIG. 24 illustrates a method for the fabrication of a lens element.

FIG. 25 illustrates the internal strains generated by the effect of impurities.

FIG. 26 illustrates the generation of compaction.

FIG. 27 illustrates the internal strains generated by the effect of compaction.

[Explanation of Reference Numerals]

1-5 OPTICAL ELEMENT

6 FIRST BODY (RETICULE)

7 SECOND BODY (WAFER)

8, 164 BIREFRINGENCE CORRECTION MEANS

10 QUARTZ GLASS

11 CENTRAL AXIS

25 DIFFRACTION GRATING

130 OPTICAL MEMBER

PL POS

FIG. 2

CENTRAL AXIS

FIG. 4

INCIDENT LIGHT POLARIZATION

CIRCUMFERENTIAL COMPONENT

RADIAL COMPONENT

FIG. 5

CENTRAL AXIS

INCOMING LIGHT

FIG. 9

REFRACTIVE INDEX

DUTY RATIO

FIG. 10

OPTICAL AXIS

PHASE DIFFERENCE

PHASE DIFFERENCE

PHASE DIFFERENCE

PHASE DIFFERENCE

FIG. 14

CENTRAL AXIS

FIG. 15

CENTRAL AXIS

CENTRAL AXIS

FIG. 19

y AXIS DIRECTION

X AXIS DIRECTION

FIG. 20

STRESS DISTRIBUTION

STRESS DISTRIBUTION

FIG. 22

CIRCUIT DESIGN

WAFER MANUFACTURE

STEP 1

STEP 3

MASK FABRICATION

STEP 2

WAFER PROCESSING (PREPROCESSING)

STEP 4

ASSEMBLY (AFTER-PROCESSING)

STEP 5

INSPECTION

STEP 6

SHIPPING

STEP 7

FIG. 23

STEP 11

OXIDATION

STEP 12

CVD

STEP 13

ELECTRODE FORMATION

STEP 14

ION IMPLANTATION

STEP 15

RESIST TREATMENT

STEP 16

EXPOSURE

STEP 17

DEVELOPMENT

STEP 18

ETCHING

STEP 19

RESIST PEELING

REPETITION